Cooperating Parties Group, Newark, New Jersey

RIVER MILE 10.9 REMOVAL ACTION NEW JERSEY

IMPACT OF RM 10.9 CAP ROUGHNESS DURING STORM CONDITIONS USING THE DELFT3D NUMERICAL MODEL OF THE UPPER LPR

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EXECUTIVE SUMMARY

A calibrated numerical model of the upper miles of the Lower Passaic River was applied to analyze the potential increase in water levels and flooding that could be associated to the placement of a sand cap at the RM 10.9 Removal Area. This analysis was requested by NJDEP Office of Dredging and Sediment Technology (ODST) to the CPG as part of the River Mile 10.9 Removal Action Project.

The model used is the calibrated Delft3D hydrodynamic model developed to support the RM 10.9 Removal Action. Although the model was developed for a different goal (to predict with high spatial resolution, the distribution of bottom shear stresses under a variety of flow conditions) it has been calibrated to reproduce accurately the hydrodynamic conditions of the upper miles of the Lower Passaic River, therefore it can also be accurately used to estimate changes in the river hydrodynamics (water levels and currents) associated to physical modifications in the river, including changes in bed material (roughness properties) in specific areas of the model domain.

Because of the uncertainty in the definition of roughness coefficient for specific material, and its relation to the model roughness, a sensitivity test was carried out where the roughness parameter at the project site was varied beyond the expected Manning roughness values for the design sand cap. Model results show that even for Manning roughness values associated to sediment with a median grain size up to two orders of magnitude larger (64 mm) than the median grain size of the designed sand cap (0.8 mm), the maximum expected increase in water levels during the peak of an extreme event (Hurricane Irene) does not exceed 0.9 inches, and it is expected to be much lower for caps with grain sizes closer to the design specification, for smaller storm events and during normal tidal conditions

An additional test was conducted to analyze the impact on hydrodynamics from an area with smoother characteristics than the rest of the river. Decreasing the Manning roughness coefficient from 0.023 to 0.018 in a full section of the river with a similar length than the RM 10.9 project area produces a negligible effect in water levels and currents downstream of the area, and a small increase in currents and associated decrease in water levels upstream of the area. Under the simulated conditions, an almost negligible impact will be expected in the river water elevations (<0.5 inches) and currents (<0.03 ft/sec) under an extreme event (Hurricane Irene)

The main conclusions drawn from this study is that for the range of conditions simulated the results obtained from the calibrated model indicate that the engineered cap at RM 10.9 even with an increase or decrease in the Manning roughness coefficient of 50% of the coefficient used in the rest of the model domain, will not have a significant (measurable) impact on flooding potential either upstream or downstream of the Removal Area, during extreme events such as Hurricane Irene, and consequently for all the range of smaller events that could be observed in the river.

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1.0 INTRODUCTION

This report presents the application of a calibrated numerical model of the upper miles of the Lower Passaic River to analyze the potential increase in water levels and flooding that could be associated with the placement of a sand cap at the RM 10.9 Removal Area. This analysis was requested by NJDEP ODST to the CPG as part of the River Mile 10.9 Removal Action Project.

To carry out the analysis the CPG used the calibrated Delft3D hydrodynamic model developed to support the RM 10.9 Removal Action. Details of the model development and calibration are presented in Section 2.0. Although the model was developed for a different goal (to predict with high spatial resolution, the distribution of bottom shear stresses under a variety of flow conditions) it has been calibrated to reproduce accurately the hydrodynamic conditions of the upper miles of the Lower Passaic River, therefore it can also be accurately used to estimate changes in the river hydrodynamics (water levels and currents) associated with physical modifications in the river including changes in bed material in specific areas of the model domain.

A sensitivity analysis using Manning values for the sand cap at RM 10.9 rougher than the expected numbers for sand from the USGS and FHWA guidance was carried out using the aforementioned model. The description of the sensitivity analysis and the results from the simulations are presented in Section 3.0. This section also includes the results from a sensitivity test using a smoother surface in a section of the river.

Finally in Section 4.0 conclusions are presented. The main conclusion of the analysis presented in this report is that for the range of conditions simulated, model results indicate that the engineered cap at RM 10.9 even with an increase or a decrease in the Manning roughness coefficient of 50% of the roughness coefficient characterizing the rest of river, will not have a significant (i.e. measurable) impact on flooding potential either upstream or downstream of the Removal Area during extreme events such as Hurricane Irene, and consequently for all the range of smaller events that could be observed in the river.

2.0 DELFT 3D MODEL OF THE LOWER PASSAIC AT RM 10.9

The primary objective of the hydrodynamic modeling development described in this section was to predict with high spatial resolution, the distribution of bottom shear stresses under a variety of flow conditions, and especially under flood events at the RM 10.9 of the Lower Passaic River. In order to resolve the features and processes that are of importance in this study (e.g. the secondary flow in the river bend, the flow distribution across the river varying from the channel to the shoals, and flow coming from the Third River) a high resolution model using the Delft3D modeling system (WL | Delft Hydraulics, 2008) was selected. The following sections describe the Delft3D system, the specific model development and the model calibration to site specific data collected in October to November 2011.

2.1 Delft3D modeling system Overview

The open source Delft-3D modeling system was chosen for its computational speed, its state-of-the-art ability to represent the essential physics of the system, and ease of model set-up. Delft3D, developed by Deltares, is a state of the art integrated surface water modeling system based on a flexible framework capable of simulating two- and three-dimensional flow, waves, water quality, ecology, sediment transport, and bottom morphology and the interactions between those processes. The system gives direct access to state-of-the-art process knowledge, accumulated and developed at one of the world's oldest and most renowned hydraulic institutes. Delft3D consists of a number of well-tested and validated modules, which are linked to and integrated with one-another.

The hydrodynamic module Delft3D-FLOW simulates two-dimensional (2D, depth averaged) or three-dimensional (3D) unsteady flow and transport phenomena resulting from tidal and/or meteorological forcing, including the effect of density differences due to a non-uniform temperature and salinity distribution (density-driven flow). This model can be used to predict the flow in shallow seas, coastal areas, estuaries, lagoons, rivers and lakes. It aims to model flow phenomena where the horizontal length and time scales are significantly larger than the vertical scales. When the fluid is regarded as vertically homogeneous with respect to temperature, salinity, and thus, density, a depth-averaged approach is appropriate. Delft3D-FLOW is able to run in two-dimensional mode (one computational layer), which corresponds to solving the depth-averaged equations.

Delft3D-FLOW's system of equations consists of the horizontal equations of motion, the continuity equation and the transport equations for conservative constituents. The equations are formulated in orthogonal curvilinear coordinates. In curvilinear coordinates, the free surface level and bathymetry are related to a flat horizontal plane of reference. Flow forcing may include tidal variation at the open boundaries, wind stress at the free surface, and pressure gradients due to free surface gradients (barotropic) or density gradients (baroclinic). Source and sink terms are included in the equations to model the discharge and withdrawal of water. Delft3D-FLOW solves the Navier Stokes equations for an incompressible fluid, under the shallow water and the Boussinesq assumptions. In the vertical momentum equation the vertical accelerations are assumed to be negligible and are neglected; this leads to the hydrostatic pressure equation.

2.2 RM 10.9 model development

2.2.1 Model Grid

Delft3D has the capability to use multiple domains within a model, transferring the momentum between domains at the interfaces. This capability is termed domain decomposition. It allows for local grid refinement without transferring the resolution to the full model domain. In addition, each domain can be parallelized on a multiple processor computer. This can significantly decrease computational time if the sub-domains are constructed at similar sizes. In this study, the model was broken up into 4 sub-domains with varying resolution. The resolution near the project site is approximately 13 m by 7 m while grids are larger in the subdomain upstream. Figure 2-1 shows the model grids and a detail of the grid at the project site near RM 10.9.

The model was used in three-dimensional mode, with a horizontal orthogonal curvilinear grid and a vertical bottom following sigma grid, with a total of ten layers. The use of a three dimensional model allows for a more accurate simulation of the vertical distribution of velocities, and some important processes such as secondary flow in the river bends.

2.2.2 Model Bathymetry

The high resolution multi-beam bathymetric survey of the area from July and August 2011 (prior to Hurricane Irene) was used to develop the model bathymetry, and was supplemented by single beam data for shoals areas that lay beyond the extent of multi-beam coverage.

2.2.3 Model Boundary conditions

The model upstream boundary condition uses the Passaic River discharge at Dundee Dam, and the downstream open boundary at RM 10.5 with water levels from the LPR RI/FS ECOM model. The inflow from the Third River was scaled to the Passaic River discharge.

2.2.4 Model Calibration

The Physical Water Column Monitoring (PWCM) data from Acoustic Doppler Current Profiler (ADCP) stations at RM 10.2 and RM 13.5 collected from October to November 2009 was used for calibrating the model. The model was calibrated by varying the Manning roughness coefficient until an optimal agreement between model and data was obtained. The Manning bottom roughness coefficient was adjusted to a value of 0.023 as part of the calibration process. The calibration period included a 6,000 cfs discharge event towards the end of the ADCP deployment, and the calibrated model was found to predict the magnitude and direction of the ebb velocities very close to the measured data. The model was further validated by comparing simulated results to velocity data collected in October and November 2011 using four different ADCPs between River Miles 10.8 and 11.1 (see Figure 2-2). This was a period of relatively low to average flow with the Passaic discharge never exceeding 3,500 cfs, and the model velocities were found to be very close to the data during this period as well. The velocity transects measured from ship-mounted ADCPs as part of the same data collection effort served to qualitatively verify the cross-shore velocity distribution predicted by the three-dimensional model. Model data comparison for the time series of water levels and bottom and surface currents at ADCP2 are presented in Figure 2-3. In addition, model and data comparison during Peak Flood and Peak Ebb at the transect on RM 10.84 are presented in Figure 2-4.

2.3 Simulation of Storm conditions

As it was previously mentioned the main objective of this model was to predict with high spatial resolution, the distribution of bottom shear stresses under a variety of flow conditions. After calibration was completed, the model was applied to simulate a one month period surrounding the Hurricane Irene event which produced nearly 25,000 cfs discharge at Dundee Dam in the Passaic River on August 31, 2011. The Irene simulation used water levels at the downstream boundary from the LPR/NB RI/FS ECOM hydrodynamic model for water year 2011, and hourly average discharge at Dundee Dam measured by the USGS gage at the upstream boundary. The model used a 1.2 second time-step, and the maximum total shear stress and velocities predicted by the model during the event were extracted. The model predicted total shear stress as high as 26 Pa in the channel near RM 10.9, and channel bottom velocities up to 2 m/s.

In addition, a synthetic 32,000 cfs event was also simulated by linearly scaling up the peak discharge of 25,000 cfs during Hurricane Irene and a surrounding 7 day period. The values of maximum total shear stress and bottom velocities in the channel near RM 10.9 predicted by the model for this synthetic event were 34 Pa and 2.3 m/s respectively.

Figure 2-1: Delft3D numerical model grid. Detail of Grid2 (RM 10.9) is shown on Top panel.

Figure 2-2: Location of fixed current measurements and transects measured during October and November 2011

Figure 2-3: Example of model calibration results at moored location ADCP2 for water levels (upper panel) and currents 0.5 m (lower panel) and 2 m (middle panel) above the bed

Figure 2-4: Example of model calibration results at transect on RM 10.94 (ADCP2) for Peak Ebb currents (Top) and Peak Flood (Bottom) currents

3.0 MODEL SENSITIVITY TO ENGINEERED CAP ROUGHNESS PARAMETER

M&N carried out a sensitivity analysis using the numerical model presented in the previous section to comply with NJDEP ODST's request to the CPG to evaluate the potential impact that the RM 10.9 engineered cap will have on the water levels upstream of the project area. As described in the previous section, the Delft3D numerical model was calibrated using a Manning roughness of 0.023 throughout the whole model domain. The calibrated Delft3D model can be used to predict changes in the hydrodynamic conditions in the model domain in response to any modifications in the river, including in this particular case the modification of the roughness in one small area (5.5 acre) of the model domain.

For the sensitivity analysis, the roughness of the cap material will be increased to values beyond the expected roughness of the proposed material. This approach is widely used to estimate the potential impact of a cap and has been used previously in the Lower Passaic River by EPA to estimate the potential increase in water levels in the Lower Passaic River as a result of the design cap for the Focus Feasibility Study (FFS) (Kim et al, 2008) (EPA, 2007)

The following sections describe the range of Manning values used in the sensitivity analysis, the results of the analysis, and an additional analysis to estimate the impact of potentially creating a smoother section of the river.

3.1 Selection of the range of Manning roughness parameter for the sensitivity simulations

The CPG has proposed in its design report (CH2M-Hill, 2013) to cover the removal site at 10.9 with a sand cap with a median grain size of 0.8 mm. Figure 3-1 shows the table from the USGS guidance WSP2339 (same as the Federal Highway and Waterways Administration Guidance FHWA-TS-84-20), where the proposed Manning roughness coefficient is associated to the median diameter or soil type. Using this table, the cap in the RM 10.9 Removal Area for a median diameter of 0.8 mm will correspond to a Manning roughness coefficient of 0.025 for a sand channel. Using the values proposed for stable channels and floodplains, the value of the Manning coefficient would vary between 0.025 – 0.032 for firm soil, and between 0.026 – 0.035 for coarse sand, with median diameters much larger than those considered in the cap. Even for the case of coarse gravel, with median grain sizes up to almost two orders of magnitude larger than 0.8 mm, the maximum proposed Manning roughness coefficient is 0.035.

It was decided that although the expected Manning roughness value based on the table in Figure 3-1 is 0.025, a sensitivity analysis with values up to 0.035 will be conducted, since this will be beyond the proposed Manning roughness value for the material used in the cap. Also it represents a nearly 50% increase in the value of the parameter from the Manning roughness value used in the rest of the model domain (0.023).

Figure 3-2 presents the maps of Manning roughness parameters used in the 4 sensitivity cases. The baseline case uses 0.023 throughout the model domain, while the other 3 cases have modified the Manning roughness parameter at the project site to values of 0.025, 0.030 and 0.035 respectively.

3.2 Sensitivity to cap roughness - Results

Results from the model simulations with the different values of Manning roughness coefficients at the RM 10.9 shoal are presented in Figure 3-3. The top panel of the figure shows the calculated water level for all the four cases at the peak of the Hurricane Irene simulation from RM 10.5 to RM 16.0. Because the differences in water level between the four cases are too small compared to the variation in water elevation from RM 10.5 to RM 16.0, the two lower panel show a detailed view of the simulated water levels for the four cases around RM 10.9 (bottom left panel) and RM 15.0 (bottom right panel). It can be observed from this figure that even for a Manning roughness coefficient of 0.035 (corresponding to a coarse gravel case), the increase in water levels caused by the RM 10.9 cap is always below one inch. Figure 3-4 presents the differences between the three cases with increased Manning roughness coefficient at RM 10.9 shoal (0.025, 0.030 and 0.035) and the baseline case with a value of 0023 throughout the model domain. Maximum differences are observed just upstream of the project area and they have a maximum value of 0.9 inches during the peak of Hurricane Irene and for the extreme cap roughness case of 0.035.

3.3 Sensitivity to a Smoother section of the River

An additional sensitivity test was carried out to estimate the potential impact in water levels and currents upstream and downstream of an area where a smoother roughness (or smoother material) is considered. Figure 3-5 shows the area of the river around RM 12.5 where the roughness coefficient in the model was modified from 0.023 to 0.018. Results are also presented in Figure 3-5. The reason that this section of river was chosen to model the impact of any potential smoothing of the river bottom are as follows:

- The downstream limit of the Delft3D model utilized in this evaluation was at RM 10.5 so, the effect of the smooth area will not be correctly simulated because water levels are prescribed at the downstream boundary, and the model results will be mainly controlled by the boundary values.
- Areas further downstream were not included in the Delft3D model's domain
- The selected area for modeling the impact of smoothing the bottom shares characteristics with the RM 10.9 Removal Area in terms of downstream river bends and downstream bridges.

Results for the Hurricane Irene simulation show that during the peak of the storm (note a different time for the peak water level and peak currents) the observed changes in currents are negligible downstream of the modified area, and a very small increase (around 0.02-0.03 feet/s) is observed upstream. In addition, water levels increase by a negligible amount downstream while they decrease by up to 0.5 inches upstream of the modified area.

Figure 3-1: Base Values of Manning's n (Source: United States Geological Survey (USGS, 1984) "Water-supply Paper 2339 - Guide for Selecting Manning's Roughness Coefficients,")

Figure 3-2: Roughness maps used in the Delft3D model for the sensitivity to cap Manning roughness simulations.

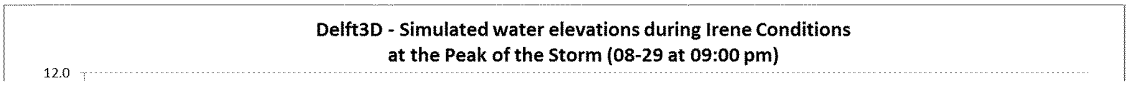

Figure 3-3: Water level results along the River from the Sensitivity analysis to cap Manning roughness in Delft3D.

Figure 3-4: Differences in water levels between baseline and the sensitivity simulations to cap Manning roughness in Delft3D.

Figure 3-5: Results from the sensitivity simulation to a smoother Manning roughness in Delft3D.

4.0 CONCLUSIONS

A numerical model using the Delft3D modeling system was constructed with the primary objective of predicting with high spatial resolution, the distribution of bottom shear stresses under a variety of flow conditions and especially under flood events at the RM 10.9 of the Lower Passaic River. The model has been successfully calibrated using a Manning roughness coefficient throughout the model domain of 0.023.

The calibrated model can be used to evaluate the impact that a change in roughness properties in an area of the model will have in the hydrodynamic conditions away from the project area, and in particular in the water elevation. Because of the uncertainty in the definition of roughness coefficient for specific material and its relation to the model roughness, a sensitivity test was carried out where the roughness parameter at the project site was varied beyond the expected Manning roughness values for the design sand cap. Even for Manning roughness values associated with sediment having a median gran size up to two orders of magnitude larger (64 mm) than the median grain size of the designed sand cap (0.8 mm) the numerical model predicts a maximum increase in water levels during the peak of an extreme event (Hurricane Irene) of 0.9 inches. Considering that for the simulated storm the differences are quite small (less than 0.9 inches), for smaller storm events, for a cap with characteristics much closer to design predictions, and during normal tidal conditions, the expected differences in water elevation will be significantly smaller.

An additional test was conducted to analyze the impact of having an area with smoother characteristics than the rest of the river. Decreasing the Manning roughness coefficient from 0.023 to 0.018 in a full section of the river with a similar length than the RM 10.9 project area produces a negligible effect in water levels and currents downstream of the area, and a small increase in currents and associated decrease in water levels upstream of the area. Under the simulated conditions, a negligible impact will be expected in the river water elevations and currents under an extreme event (Hurricane Irene)

For the range of conditions simulated and presented in this document, model results indicate that the engineered cap at RM 10.9, even with an increase in the Manning roughness coefficient of 50% compared to the coefficient used in the calibrated model to represent the rest of river, will not have a significant (measurable) impact on flooding potential either upstream or downstream of the Removal Area, during extreme events such as Hurricane Irene and consequently for all the range of smaller events that could be observed in the river.

5.0 REFERENCES

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